

Proceedings of GT2007
ASME Turbo Expo 2007: Power for Land, Sea and Air
May 14–17, 2007, Montreal, Canada

GT2007–27914

A PROBABILISTIC SYSTEM ANALYSIS OF INTELLIGENT PROPULSION SYSTEM TECHNOLOGIES

Michael T. Tong

National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

ABSTRACT

NASA's Intelligent Propulsion System Technology (*Propulsion 21*) project focuses on developing adaptive technologies that will enable commercial gas turbine engines to produce fewer emissions and less noise while increasing reliability. It features adaptive technologies that have included active tip-clearance control for turbine and compressor, active combustion control, turbine aero-thermal and flow control, and enabling technologies such as sensors which are reliable at high operating temperatures and are minimally intrusive. A probabilistic system analysis is performed to evaluate the impact of these technologies on aircraft CO₂ (directly proportional to fuel burn) and LTO (landing and takeoff) NO_x reductions. A 300-passenger aircraft, with two 396-kN thrust (85,000-pound) engines is chosen for the study. The results show that NASA's Intelligent Propulsion System technologies have the potential to significantly reduce the CO₂ and NO_x emissions. The results are used to support informed decision-making on the development of the intelligent propulsion system technology portfolio for CO₂ and NO_x reductions.

Keywords: NASA, intelligent propulsion system technologies, propulsion 21, probabilistic, system analysis, fuel burn, CO₂, LTO NO_x

INTRODUCTION

The continuing growth in air traffic and increasing public awareness have made environmental considerations one of the most critical aspects of commercial aviation today. As aviation grows, we must reduce aircraft noise and emissions from airports, due to the increasing concern over local air quality, climate change and health effects of emissions. It is generally recognized that significant improvement to the environmental acceptability of aircraft will be needed to sustain long term growth. Improved environmental protection will be a vital element to ensure U.S. air transportation viability and global leadership.

NASA's Intelligent Propulsion System Technology (*Propulsion 21*) project focuses on developing adaptive technologies that will enable commercial gas turbine engines to

reduce fuel burn, produce fewer emissions and less noise while increasing reliability. The entry into service date for most of these technologies was targeted for 2008 to 2012. The *Propulsion 21* project features adaptive technologies that include:

<u>Tech no.</u>	<u>Technology name</u>
tech-1	Active tip-clearance control for fan
tech-2	Active tip-clearance control for high-pressure compressor (HPC)
tech-3	Active tip-clearance control for high-pressure turbine (HPT)
tech-4	Active tip-clearance control for low-pressure turbine (LPT)
tech-5	Active flow control for LPC
tech-6	Active flow control for HPC
tech-7	Turbine aero-thermal and flow control for HPT and LPT
tech-8	Active combustion control for lean direct injection (LDI) combustor
tech-9	Smart fan containment system
tech-10	High-temperature wireless data communication technology

These technologies are described in Table 1.

A probabilistic system assessment is performed to evaluate the impact of these adaptive technologies on aircraft fuel-burn and LTO NO_x reductions. The statistical approach quantifies the uncertainties inherent in these new technologies and their influence on the likely outcomes of engine performance. Consequently, it provides additional insight into the risks associated with new technologies, which are often needed by the decision-makers to determine the benefit and return-on-investment of new propulsion technologies. The results are used to support informed decision-making on the development of the intelligent propulsion system technology portfolio for CO₂ and NO_x reductions.

TABLE 1.—DESCRIPTION OF INTELLIGENT PROPULSION SYSTEM (ADAPTIVE) TECHNOLOGIES

Tech no.	Technology description
tech-1	<i>Active tip clearance control applied to the fan casing</i> —this technology has an estimated gain on fan efficiency. The fan casing is constructed with shape memory alloy (SMA) and actively controlled through electric heating. A weight increase is assumed for the casing.
tech-2	<i>Active tip clearance control applied to the high-pressure compressor (HPC) casing</i> —this technology has an estimated increase on HPC efficiency. The clearance control, utilizing SMA, is added to all stages.
tech-3	<i>Active tip clearance control applied to the high-pressure turbine (HPT)</i> —the SMA material is envisioned to be applied to the casing. The turbine is sufficiently hot enough that the SMA material would be passively controlled by the temperature difference between takeoff and cruise. This technology’s primary benefit is an efficiency increase for the HPT of a deteriorated engine.
tech-4	<i>Active tip clearance control applied to the low-pressure turbine (LPT)</i> —this technology has the same properties and benefits as the one for the HPT.
tech-5	<i>Active flow control applied to LPC</i> — active and passive flow control technology to enable higher LPC blade loading, improved compressor efficiency and operation stability.
tech-6	<i>Active flow control applied to HPC</i> — this technology has the same properties and benefits as the one for the LPC.
tech-7	<i>Turbine aerothermal and flow control technology for HPT and LPT</i> —to develop flow control schemes in turbines to enable safer operation of highly loaded blades in high/low pressure components.
tech-8	<i>Active combustion control technology for lean direct injection (LDI) combustor</i> —provides closed loop, dynamic control of fuel injection, fuel air mixing, and staging of fuel sources. It focuses on 3 areas: combustion instability control, burner pattern factor control, and emission minimizing control. The technology is focused primarily on NO _x reduction.
tech-9	<i>Smart fan-containment system</i> —smart material/structural concepts for improved (lighter) weight, impact damage tolerance, and noise-reducing fan containment case.
tech-10	<i>High-temperature wireless data communication technology</i> —electronics with a high-temperature capability (~600 °C) for wireless power transmission and data communication.

ADAPTIVE ENGINE TECHNOLOGIES

Numerous technologies are under development to adaptively modify turbine engine performance. These adaptive technologies can lead to improved engine component efficiency and/or reduced airplane empty weight, both resulting in overall fuel burn reduction. As a rule of thumb, for a large subsonic aircraft a 1000 pound reduction in weight yields a 0.5 to 0.7% reduction in jet fuel consumed. For carbon based fuels, there is a 1:1 relationship between the amount of fuel burned and the amount of CO₂ generated.

The primary classes of adaptive technologies are flow control, structural control, combustion control, and also enabling technologies that are applicable to each.

Flow Control

Flow control technologies directly manipulate air flow through or around a specific engine component. The manipulation is enacted by actively injecting or extracting air, by inserting small mechanical protuberances into the flow, or by using plasma actuators. Injected air can be supplied by bleed from a rear compressor stage, or by forming “synthetic” jets from a local cavity with an oscillating membrane that cyclically entrains and discharges air. Air injection is then used to energize low momentum regions within the main flow. The protuberances can be actively inserted and retracted based on flow conditions, or they can be designed to passively react to the flow; in both cases the intent is to influence boundary

layer separation. Plasma actuators employ electrical actuation rather than pneumatic.

Flow control can be used to improve compressor performance by sensing pressure disturbances preceding flow separation, then energizing the air ahead of the separation line. Flow can be controlled through the airfoil to improve flow quality, and in the end-wall region to enable safe compressor operation at reduced stall margins. Both offer the potential to increase aerodynamic loading per blade without reducing aerodynamic efficiency, and thus offer the promise of reducing the number of airfoils (and therefore compressor weight) needed to achieve a given pressure ratio [1, 2]. Reduced stall margins can also enable compressor operation closer to the peak efficiency operating point. For a large subsonic aircraft engine, compressor stages can be 15% of the engine’s weight, and a 1% improvement in high-pressure compressor efficiency can lead to 2% reductions in fuel burn.

Flow control can be used to cool structures as well, such as closed-loop cooling control for turbine blades. By sensing hot-spots as they occur and only cooling as necessary, the total mass of bleed air can be reduced. Bleeding air from the compressor directly reduces the percentage of inlet air available for combustion, so bleed air reduction translates directly into propulsion efficiency improvement.

Structural Control

Actively controlling the clearances between rotating blades and shrouds directly improves fan, compressor, and turbine

efficiency by reducing leakage through the clearances at each stage. Current engines are designed with sufficient clearance to minimize rubbing during flight. Typically these clearances are sized to prevent rubbing during take-off, and are thus larger than necessary during cruise. Excess clearance allows leakage through the gap, diverting air away from its intended path through the core or bypass ducts. Current open-loop clearance control systems use compressor and/or fan bleed air to cool the case during cruise and therefore close the gap. Closed-loop clearance control promises finer control of the gap while preventing rub-induced component degradation. For a large subsonic aircraft engine, each 10 mils of excess clearance increases specific fuel consumption by roughly 1%. This will require an increase in exhaust gas temperature margins by about 10 °C [3], in order to maintain the same engine thrust level. The ability to maintain tight clearances can provide both a substantial fuel-burn reduction and increased engine life. These closed-loop active clearance control systems require robust, accurate and precise sensors and actuators [4].

Combustion Control

Combustion control technologies are being developed to both enable lean-burning combustors and to directly control the local combustion process thus providing more uniformly efficient burning. A new generation of lean-burning combustors is being developed to reduce emissions, but they are more susceptible to combustion instability and flame-out [5]. Active combustion control provides closed-loop, dynamic control of fuel injection, fuel air mixing, and fuel source staging to disrupt the coupling between the combustion process and combustor acoustics leading to instabilities [6]. Pressure sensors are used to monitor the combustor acoustics, and control laws are used to dynamically modulate high-response-rate actuators in the fuel line. To achieve fine control of the spatial distribution of fuel, sensor arrays are used to determine the combustor cross-sectional temperature distribution for use in closed-loop fuel injector control.

“Pattern factor” control is also being investigated to produce spatially uniform combustion, eliminating hot and cold spots that generate NO_x and CO₂ emissions, respectively. Sensors determine either the local temperature distribution across a cross-section of the combustor, or sense emissions directly for use in closed-loop fuel injector control [7].

Enabling Technologies

Adaptive control can be either active or passive. Passive techniques include self-triggered mechanisms such as thermally-triggered shape memory alloys or microstructures triggering flow disturbances after a specific velocity has been reached. Active techniques require at a minimum a sensor, control logic, and an actuator. To achieve these, some subset of sensors, electronics, materials, actuators, wireless communications, power generation, and control logic are required. These technologies do not reduce emissions on their own, but they are critical for the practical embodiment of the aforementioned flow, structural, and combustion control technologies that directly reduce emissions.

Specific sensors of use for adaptive engine components include: temperature and pressure sensors (both static and dynamic), surface and gas; mass flow, surface strain, and blade tip clearance sensors. Applications exist for each of these sensors throughout the engine, including the hot sections of the turbine and nozzle. In addition, specialized sensors for the combustor include fuel flow, chemical species, and temperature sensors that can withstand high temperatures (typically 1000 °C) and can operate in the presence of by-products from burning jet fuel. Not only the sensors need to operate at elevated temperatures; each sensor system typically includes processing electronics, and weight is reduced (hence fuel-burn reduced) by using wireless communications and locally-scavenged power [8]. Actuators are needed for flow control in the inlet, fan, compressor, and turbine; clearance control in the compressor and turbine; and for fuel modulation. Desirable actuator characteristics include fast response times, low weight and bulk, and reliable operation in the engine environment. Active materials such as piezoelectric and shape memory alloys can be used as both actuators and sensors, including in the hot sections [9, 10].

Finally, control logic must also be included as a critical component of any actively controlled system. Aircraft engines are complex, nonlinear systems with significant interaction between components. Multivariable control methods provide the ability to optimize the performance of the whole system [11] and/or the performance of individual components [12, 13].

ANALYSIS APPROACH AND PROCEDURES

Expert Opinion Elicitation

As Rand analyst E.S. Quade observed about 30 years ago, “Intuition and judgment permeate all analysis... As questions get broader, intuition and judgment must supplement quantitative analysis to an increasing extent” [14]. Expert opinions are an appropriate means of decision support when the scientific research contains few high-quality scientific studies and a valid research synthesis cannot be conducted—a situation that often occurs during the early or “emerging” phase of a technology. Expert judgment must be used to judge the risks of emerging technology. An effective expert opinion elicitation process, or technology audit, is crucial for performing technology assessment. More details on the utilization of expert opinion can be found in references [15] and [16].

For the current assessment, a technology audit scheme (TAS) based on the Delphi method [17] is used to elicit opinions from the NASA technologists identified as the focal point for each of the technologies. The Delphi method is a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires and interviews interspersed with controlled opinion feedback. The focus of the TAS is to identify the applicable set of intelligent propulsion system technologies for the vehicle of interest, gather the required information, and compile the data necessary for the system analysis.

The Beta Distribution

Based on the information obtained from the technologists, the 3-point estimates (maximum, minimum, and most-likely values) of the impacts (positive and/or negative) for each of the technologies are quantified. They are summarized in Table 2.

For the current assessment, the beta distribution is used to quantify the uncertainties. In practice, in the absence of real measured data, one should try different distributions to see if the results change significantly. If they do, more expert opinions are needed.

A four-parameter beta distribution is created for each of the technologies. The probability density function (PDF) of the beta distribution is:

$$f(x) = \frac{1}{B(p, q)} \frac{(x-a)^{p-1} (b-x)^{q-1}}{(b-a)^{p+q-1}} \quad (1)$$

and the cumulative density function (CDF) is

$$CDF(t) = \frac{1}{B(p, q)} \int_0^t y^{p-1} (1-y)^{q-1} dy \quad (2)$$

with the transformation

$$t = \frac{(x-a)}{(b-a)}$$

where the parameters a and b are the minimum and maximum values of the variable x , respectively; p and q are the distribution shape parameters and B is the beta function defined by

$$B(p, q) = \frac{\Gamma(p) \Gamma(q)}{\Gamma(p+q)} = \int_0^1 t^{p-1} (1-t)^{q-1} dt \quad (3)$$

The shape parameters p and q depend on whether the mode (most-likely value) is to the left or right of the midrange, as shown in Figure 1. They are determined using the method described in [18].

These three equations are solved numerically, and are coupled with the Fast Probability Integration (FPI) computer code [19]. Together, they are used to perform the probabilistic system simulation of the intelligent propulsion system technologies.

System Analysis

In an era of shrinking development budgets and resources, a system analysis, performed in the early stages of a technology program, is critical to the successful development of new aeronautics technologies. It assesses the impact of a new technology on the aircraft system, in terms of the metrics such as fuel burn, emissions and noise reductions, etc.

For the current assessment, the system analysis simulates the thermodynamic cycle using NPSS (Numerical Propulsion System Simulation) [20], engine weight estimation is done using WATE (Weight Analysis of Turbine Engines) [21, 22],

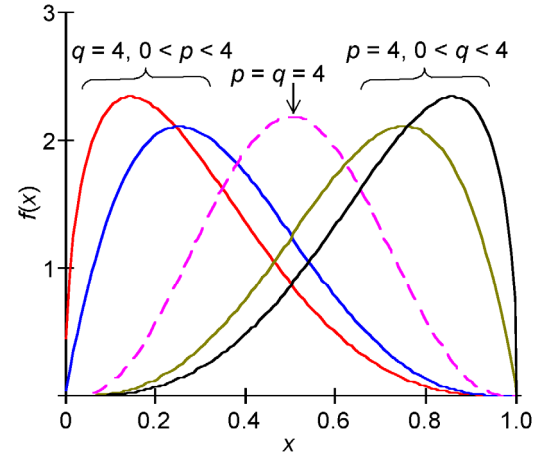


FIGURE 1.—THE BETA DISTRIBUTION FOR VARIOUS VALUES OF ITS SHAPE PARAMETERS p AND q (HOLLAND, 2002).

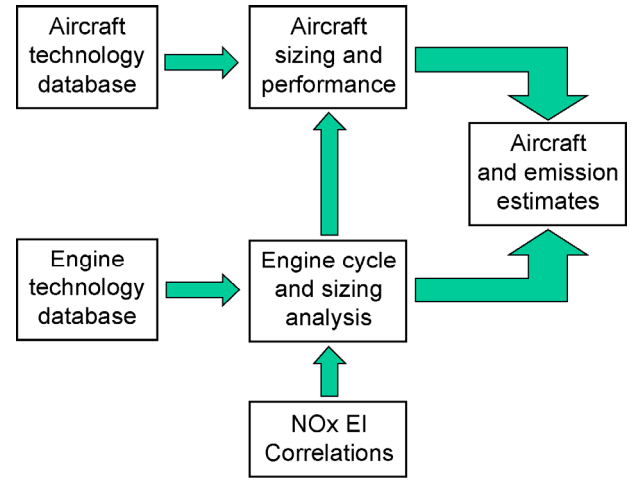


FIGURE 2.—SYSTEM ANALYSIS SCHEMATIC.

and aircraft mission sizing is done using FLOPS (FLight OPTimization System) [23]. A schematic of the integrated approach is shown in Figure 2.

The computer code NPSS is used to calculate engine thrust, specific fuel consumption and LTO NO_x emissions.

The engine weight is calculated by the WATE code. The results from NPSS and WATE are used by FLOPS for performing airplane mission and sizing analyses, and ultimately calculate the CO₂ emission (or fuel-burn) based on a 5556-kilometers (3000 nautical miles) economic mission. The wing size and the engine size are parametrically varied to obtain a minimum gross weight airplane.

Probabilistic Analysis

In a system analysis that involves several design parameters, X_i , with uncertainties, it is often desired to find the probability of achieving response value (Z) below a critical value of interest Z_0 . This critical value can be used to form a limit state function $g(X)$, which can be described as:

$$g(X) = Z(X_1, X_2, X_3, \dots, X_n) - Z_0 \quad (4)$$

TABLE 2.—INTELLIGENT PROPULSION SYSTEM TECHNOLOGIES AND THEIR UNCERTAINTIES FOR A LARGE SUBSONIC TRANSPORT

Technology identification	Technology	Baseline value	Maximum benefit (and/or minimum penalty)	Minimum benefit (and/or maximum penalty)	Most-likely benefit (and/or most-likely penalty)
tech-1	Active tip-clearance control for fan	0.90 fan poly. eff., 7435 kg (16392 lbs.) engine dry weight, 74.5 kW (100 hp) power extraction total for the system	+1.00 pt fan poly. eff., +9 kg (+15 lbs) eng. wt. +0.37 kW (0.5 hp) power requirement	+0.00 pt fan poly. eff., +15 kg (+25 lbs) eng. wt. +1.12 kW (1.5 hp) power requirement	+0.50 pt. fan poly. eff., +12 kg (+20 lbs) eng. wt. +0.75 kW (1 hp) power requirement
tech-2	Active tip-clearance control for HPC	0.90 HPC poly. eff., 7435 kg (16392 lbs.) engine dry weight,	+0.50 pt HPC poly. eff, +6 kg (10 lbs) engine wt. +0.37 kW (0.5 hp) power requirement	+0.25 pt HPC poly. eff., +12 kg (20 lbs) engine wt. +0.75 kW (1 hp) power requirement	+0.40 pt HPC poly. eff., +9 kg (15 lbs) eng. wt. +0.37 kW (0.5 hp) power requirement
tech-3	Active tip-clearance control for HPT	0.93 HPT adia. eff.	+1.00 pt HPT adia. eff +6 kg (10 lbs) engine wt.	+0.65 pt HPT adia. eff. +12 kg (20 lbs) engine wt.	+0.90 pt HPT adia. eff +9 kg (15 lbs) engine wt.
tech-4	Active tip-clearance control for LPT	0.93 LPT adia. eff.	+0.20 pt. LPT adia. eff. +6 kg (10 lbs) engine wt.	+0.00 pt. LPT adia. eff. +12 kg (20 lbs) engine wt.	+0.10 pt. LPT adia. eff. +9 kg (15 lbs) engine wt.
tech-5	Active flow control for LPC	0.90 LPC poly. eff.	+2.0 pt. LPC poly. eff	+1.0 pt. LPC poly. eff	+1.5 pt. LPC poly. eff
tech-6	Active flow control for HPC	0.90 HPC poly. eff.	+2.0 pt. HPC poly. eff	+1.0 pt. HPC poly. eff	+1.5 pt. HPC poly. eff
tech-7	Turbine aero-thermal and flow control for HPT and LPT	1449 °C (2640 °F) T41, 23% of HPC flow used for turbine cooling	+222°C (400°F) T41, +1 pt. HPT adia. eff, reduce turbine cooling by 25%, +2 pt. LPT adia. eff.	+56°C (100°F) T41, +.25 pt. HPT eff, reduce turbine cooling by 5%, +1 pt. LPT eff.	+83°C (150°F) T41, +.5 pt. HPT eff, reduce turbine cooling by 10%, +1.5 pt. LPT eff.
tech-8*	Active combustion control for LEI combustor	LTO NOx -31.5% below 1996 ICAO rule, 7435 kg (16392 lbs.) engine dry weight,	Additional 6% LTO NOx reduction, -33°C (-60°F) T4 margin , +9 kg (+15 lbs) eng. wt., +1 HP power requirement	Additional 2% LTO NOx reduction, -11°C (20°F) T4 margin , +15 kg (+25 lbs) eng. wt., +2 HP power requirement	Additional 4% LTO NOx reduction, -22°C (40°F) T4 margin , +12 kg (+20 lbs) eng. wt., +1.5 HP power requirement
tech-9	Smart fan containment system	2768 kg/m ³ (0.1 lbs/in ³) case material density	–50% fan case wt.	–10% fan case wt.	–25% fan case wt.
tech-10	High-temperature wireless data communication technology	7435 kg (16392 lbs.) engine dry weight	–113 kg (–250 lbs) engine wt.	–48 kg (–105 lbs) engine wt.	–77 kg (–170 lbs) engine wt.

*Note: benefit due to control/adaptive technology only; benefit of LEI combustor technology not considered

where values of $g(X) \geq 0$ are undesirable. Here the objective would be to compute probability $P[g(X) \leq 0]$. Given the joint probability density function $f_X(x)$ of the limit state function $g(x)$, we can formulate the limit-state probability $P[g \leq 0]$ as

$$P = P[g(X) \leq 0] = \int_{\Omega} \dots \int f_X(x) dx \quad (5)$$

where Ω describes the domain of integration. This multiple integration is, in general, very difficult to integrate analytically. Many approximation methods, such as Monte Carlo simulation, have been developed to evaluate the equation (5).

All probabilistic analysis methods are approximate. Monte Carlo simulation, which is oftentimes referred to as the “exact” solution, is actually an approximate because a finite number of samples are always used. Thus, the nature of the approximation is one of “lack of data”, which can be reduced by increasing the number of samples. However, for large-scale high fidelity problems, the inefficiency of Monte Carlo simulation renders it impractical for use. Many efficient methods have been developed to alleviate the need for Monte Carlo simulation. These methods include the first and second-order reliability method (FORM and SORM) [24], the advanced mean value family of methods (AMV) [25], and the response surface method (RSM) [26]. These methods replace the original deterministic model with a computationally efficient analytical model in order to speed up the analysis.

For more than a decade NASA Glenn has been engaged in developing efficient probabilistic methods. As a result of this intensive effort, the computer code, FPI (fast probability integration), was developed to solve a large class of engineering problems. FPI was developed by Southwest Research Institute for NASA Glenn [27]. It offers several techniques to find the probability of a given limit state function value for the response function. For the current assessment, an advanced first-order reliability method is used. This method, based on the most-probable-point (MPP) concept frequently used in structural reliability analysis, is one of the several methods in the FPI code. The role of FPI is to perform probabilistic analysis utilizing the results generated by NPSS, WATE, and FLOPS. The results are generated in the form of cumulative distribution functions (CDFs). A schematic of the integrated approach is shown in Figure 3.

LTO NO_x Emissions

The LTO (landing and takeoff) NO_x emissions are computed based on engine fuel flow and the combustor emission index (EI). Fuel flow itself is a strong function of power setting during the LTO cycle, which involves four different throttle modes mandated by the ICAO (International Civil Aviation Organization): 10% (takeoff), 85% (climb), 30% (approach), and 7% (idle). Time in mode is simulated as follows: 0.7 minute for takeoff, 2.2 minutes for climb, 4 minutes for approach, and 26 minutes for taxi-ground idle. The sum of the emissions at these four conditions is used to determine the amount of NO_x emitted per LTO cycle. The calculation is:

$$\text{LTO NO}_x = \sum \text{fuel flow} \times \text{EI}_{\text{NO}_x} \times \text{time in mode} \quad (6)$$

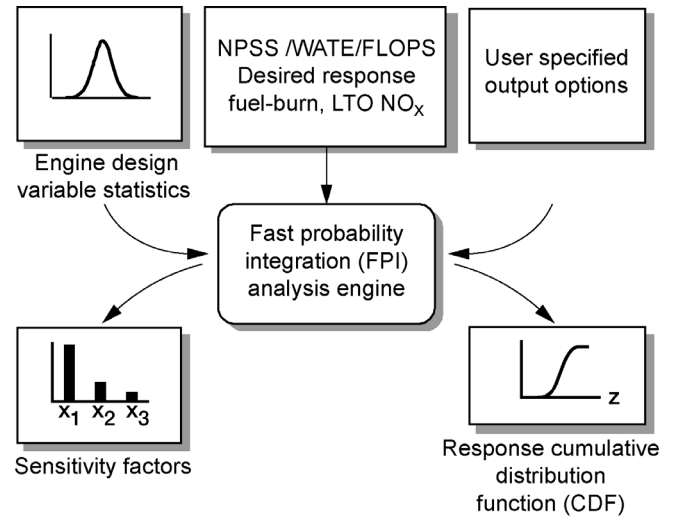


Figure 3.—Fast probability integration input/output schematic.

The EI correlation used for the current calculation is based on the lean combustor flame-tube tests [28] and is defined as:

$$\text{EI}_{\text{NO}_x} = K(P_{t3})^{0.5945} \exp[(T_{t3} - 459.67)(0.002867)] \times (\text{FAR}/\text{delphi})^{1.6876} [(1 - P_{t4}/P_{t3}) \times 100]^{-0.5651} \quad (7)$$

where

K	technology constant
P_{t3}	combustor inlet total pressure, psia
P_{t4}	combustor exit total pressure, psia
T_{t3}	combustor inlet total temperature, Rankine
FAR	fuel air ratio
delphi	1 – fraction of combustor inlet air used for liner cooling

RESULTS AND DISCUSSION

The results of individual technology impacts on aircraft CO₂ emission, at 75% and 95% probability levels, are shown in Figure 4. They are relative to those of the current state-of-the-art 300-passenger airplane (baseline). They show that all of the adaptive technologies are beneficial toward reducing CO₂ emissions, with flow control technologies, *turbine aero-thermal and flow control for HPT and LPT* (tech-7) and *active flow control for HPC* (tech-6), show particular promise. For the structural control technologies, a large benefit is possible from the *advanced HPT tip-clearance control technology* (tech-3). The impact of *active tip-clearance control technologies for fan and HPC* (tech-1 and tech-2) are moderate. The *active combustion control technology* (tech-8) shows relatively small CO₂ reductions, but its target benefit is NO_x reduction which is also shown here. Other technologies have minimal benefit on CO₂ reduction. Cumulatively at 95% probability level, the ten adaptive technologies can potentially reduce CO₂ emission by 9.6%, as shown in Figure 5.

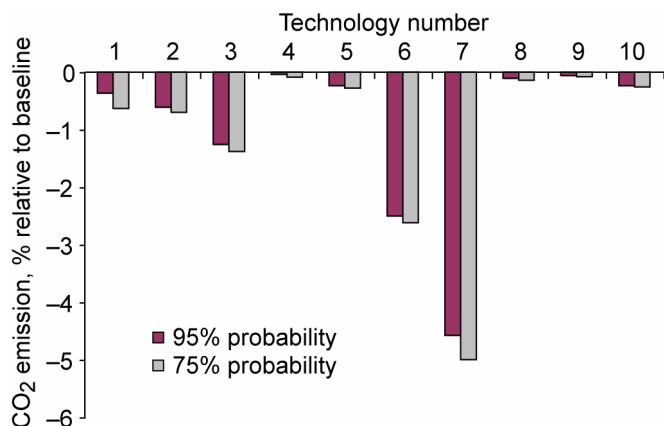


Figure 4.—INDIVIDUAL TECHNOLOGY IMPACTS ON AIRCRAFT CO₂ EMISSION.

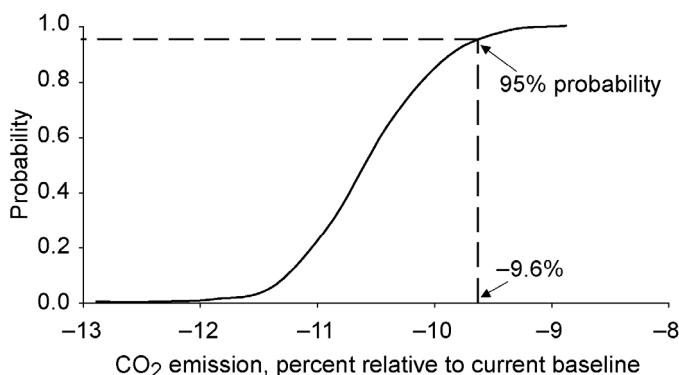


FIGURE 5.—CUMULATIVE DISTRIBUTION FUNCTION (CDF) OF AIRCRAFT CO₂ EMISSION.

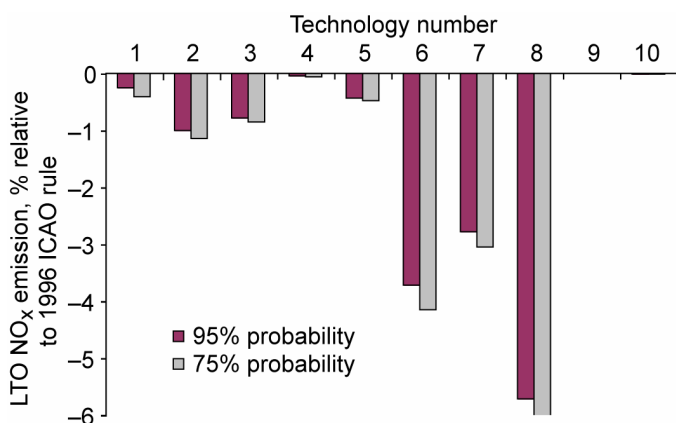


Figure 6.—INDIVIDUAL TECHNOLOGY IMPACTS ON LTO NO_x EMISSION.

The results of individual technology impacts on LTO NO_x emission, at 75% and 95% probability levels, are shown in Figure 6. They are relative to the 1996 ICAO rule. They results show that the *active combustor control for LDI combustor* (tech-8) has the biggest benefit. The *active flow control for HPC* (tech-6) and *turbine aero-thermal and flow control for HPT and LPT* (tech-7) also provide significant benefit. These two flow-control technologies decrease the SFC

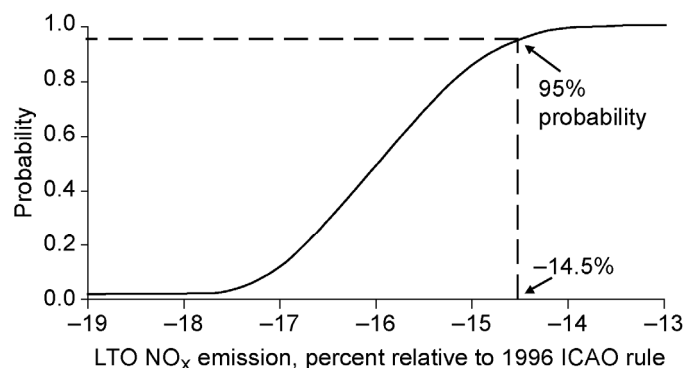


FIGURE 7.—CUMULATIVE DISTRIBUTION FUNCTION (CDF) OF LTO NO_x EMISSION.

(specific fuel consumption) significantly, which also decrease the LTO NO_x. The other technologies have minimal or no impact on the LTO NO_x emissions. Cumulatively at 95% probability level, the ten adaptive technologies can potentially reduce NO_x emission by 14.5%, as shown in Figure 7.

Note that the benefit of the LDI combustor itself is not considered. The current assessment focuses only on the adaptive/control technologies. Also, all the technology evaluations were based on new engines, using existing baseline engine design. The inclusion of engine degradation models will show significant additional emission-reduction benefits because adaptive technologies inherently compensate for many forms of degradation, such as erosion and wear.

CONCLUSIONS

A probabilistic system analysis has been performed to assess the impact of a variety of adaptive engine technologies on aircraft CO₂ and NO_x emissions. CO₂ reduction was modeled as directly proportional to reduced fuel burn. The results show that the adaptive technologies described here reduce fuel burn and emissions by reducing engine and aircraft weights, improving propulsion efficiency, and better combustion control, and have the potential to significantly reduce aircraft CO₂ and NO_x emissions. As a group, the flow-control technologies are the most beneficial for CO₂ reduction. They also provide significant benefit for LTO NO_x reduction. For the structural-control technologies, a large benefit is possible from the HPC tip-clearance control technology. For NO_x reduction, the combustion control technology shows the biggest benefit.

These adaptive technologies described are relatively undeveloped, so the results presented are based on expert predictions of expected benefits and penalties. The fidelity of these assessments will continue to improve as more experimental data becomes available showing measured performance in relevant conditions.

Also, the degree of difficulty (or cost) in technology development and implementation has not been considered in the current study. To prioritize the development of the most promising technologies for CO₂ and NO_x reductions, a cost-benefit analysis should also be performed.

ACKNOWLEDGMENTS

The author thanks Jeffrey Berton, William Haller, Scott Jones, and Carolyn Mercer of NASA Glenn Research Center for providing inputs to this paper. Thanks also to Michelle Kirby of Georgia Institute of Technology for many valuable discussions and collecting the assessment data.

REFERENCES

- [1] Culley, D.E., Bright, M.B., Prahst, S.P., Strazisar, A.J., "Active Flow Separation Control of a Stator Vane using Embedded Injection in a Multistage Compressor Experiment," ASME Journal of Turbomachinery, vol. 126, pp. 24–34, January 2004.
- [2] Strazisar, A.J., Bright, M.M., Thorp, S., Culley, D.E., Suder, K.L., "Compressor Stall Control through Endwall Recirculation," Proceedings of ASME Turbo Expo 2004, Vienna, Austria, 2004.
- [3] Wiseman, M.W., Guo, T., "An Investigation of Life Extending Control Techniques for Gas Turbine Engines," Proceedings of the American Control Conference, IEEE Service Center, Piscataway, NJ, IEEE Catalog No. 01CH37148, vol. 5, pp. 3706–3707, 2001.
- [4] Lattime, S.B., Steinetz, B.M., "High-Pressure-Turbine Clearance Control Systems: Current Practices and Future Directions," Journal of Propulsion and Power, vol. 20, no. 2, March-April 2004, pp. 302–311 also NASA/TM—2002-211794.
- [5] Tacina, R., Wey, C., Laing, P., Mansour, A., "A Low NO_x Lean-Direct Injection, Multipoint Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines," NASA/TM—2002-211347, April 2002.
- [6] DeLaat, J.C., Chang, C.T., "Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines," presented at the 16th International Symposium on Air breathing Engines, Cleveland, Ohio, August 31-September 5, 2003.
- [7] McCarty, B., Tomondi, C., McGinley, R., "Reliable and Affordable Control Systems Active Combustor Pattern Factor Control," NASA/CR—2004-213097 (2004).
- [8] Hunter, G.W., Wrbanek, J.D., Okojie, R.S., Neudeck, P.G., Fralick, G.C., Chen, L., Xu, J., Beheim, G.M., "Development and application of high-temperature sensors and electronics for propulsion applications," Proc. SPIE 6222 (2006).
- [9] Noebe, R.D., Gaydosch, D., Padula II, S.A., Biles, T., Garg, A., "Properties and Potential of Two (Ni,Pt)Ti Alloys for Use as High-Temperature Actuator Materials," Proc. SPIE 5761. 2005.
- [10] Sayir, A., Farmer, S.C., Dynys, F.W., "High-Temperature Piezoelectric Ceramic Developed," Research & Technology 2004, NASA/TM—2005-213419 (2005).
- [11] Litt, J.S., Simon, D.L., Garg, S., Guo, T.-H., Mercer, C., Millar, R., Behbahani, A., Bajwa, A., Jensen, D.T., "A Survey of Intelligent Control and Health Management Technologies for Aircraft Propulsion Systems," NASA/TM—2005-213622, 2005.
- [12] Bright, M.M., Culley, D.E., Braunscheidel, E.P., Welch, G.E., "Closed Loop Active Flow Separation Detection and Control in a Multistage Compressor," Prepared for the 43rd Aerospace Sciences Meeting and Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 10–13, 2005, NASA/TM—2005-213553, AIAA-2005-0849.
- [13] Le, D.K., DeLaat, J.C., Chang, C.T., Vrnak, D.R., "Model-Based Self-Tuning Multiscale Method for Combustion Control," Prepared for the 41st Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Tucson, Arizona, July 10–13, 2005, NASA/TM—2006-213855. AIAA-2005-3593.
- [14] Millett, Stephan M. and Honton, Edward J., "A Manager's Guide to Technology Forecasting and Strategic Analysis Methods," Battelle Press, 1991.
- [15] R.L. Keeney and D. von Winterfeldt, "Eliciting Probabilities from Experts in Complex Technical Problems," IEEE Transaction on Engineering Management, 38, 191–201, 1991.
- [16] S. Kaplan, "Expert Information vs. Expert Opinions: Another Approach to the Problem of Eliciting/Combining Using Expert Knowledge in PRA," Reliability Engineering and System Safety, 25, 61–72, 1992.
- [17] Sackman, H., "Delphi Assessment: Expert Opinion, Forecasting, and Group Process." Rand report R-1283-PR, Rand Corporation, April 1974. Santa Monica, CA.
- [18] Holland, Frederic A., "A Simple Method for Estimating the Parameters of the Beta Distribution Applied to Modeling Uncertainty in Gas Turbine Inlet Temperature," ASME Turbo Expo Paper GT-2002-30295.
- [19] Southwest Research Institute: FPI User's and Theoretical Manual, San Antonio, TX, 1995.
- [20] NASA-Industry Cooperative Effort: "Numerical Propulsion System Simulation User Guide and Reference," Software Release NPSS 1.5.0, May 7, 2002.
- [21] Onat, E. and Klees, G.W., "A Method to Estimate Weight and Dimensions of Large and Small Gas Turbine Engines," NASA CR-159481, 1979.
- [22] A Computer Code for Gas Turbine Engine Weight and Life Estimation. Michael T. Tong, Ian Halliwell, Louis Ghosn. ASME Journal of Engineering for Gas Turbine and Power, vol. 126, no. 2, April 2004.

[23] McCullers, L.A., "Flight Optimization System User's Guide, Version 5.85," NASA Langley Research Center, 1998.

[24] Madsen, H.O., Krenk, S., and Lind, N.C., "Methods of Structural Safety," Prentice-Hall, Inc., New Jersey, 1986.

[25] Wu, Y.-T., Millwater, H.R., and Cruse, T.A., "Advanced Probabilistic Structural Analysis Methods for Implicit Performance Functions," AIAA Journal, 28, no. 9, September 1990.

[26] Faravelli, L., "Response Surface Approach for Reliability Analysis," Journal of Engineering Mechanics, 115, no. 12, 1989.

[27] Southwest Research Institute, "Probabilistic Structural Analysis Methods (PSAM) for Select Space Propulsion System Components," Final Report NASA Contract NAS3-24389, NASA Glenn Research Center, 1995.

[28] Tacina, R., Mao, C., and Wey, C., "Experimental Investigation of a Multiplex Fuel Injector Module with Discrete Jet Swirlers for Low Emission Combustors," AIAA-2004-0185.